"Die-Sinking EDM Machining of Inconel 718: A Comprehensive Analysis of Machinability Characteristics"

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1. Introduction

Inconel 718 is a nickel-based superalloy extensively used in aerospace, defense, nuclear, and gas turbine industries owing to its exceptional mechanical strength, high-temperature stability, creep resistance, and corrosion performance. These superior characteristics arise from its complex metallurgical composition, γ–γ′ matrix strengthening mechanism, and precipitation-hardened microstructure. However, the same properties that make Inconel 718 attractive for high-performance engineering applications also make it extremely difficult to machine using traditional techniques. During conventional machining processes, the alloy's low thermal conductivity, high work-hardening tendency, and strong affinity for tool materials result in rapid tool wear, elevated cutting forces, dimensional inaccuracy, and severe thermal distortion. This challenge increases machining cost, reduces productivity, and limits the manufacturability of intricate geometries.

Die-sinking Electrical Discharge Machining (EDM) has emerged as an effective non-traditional machining technique capable of processing electrically conductive and difficult-to-cut materials like Inconel 718 irrespective of their mechanical or thermal properties. In die-sinking EDM, material removal occurs due to controlled and repeated spark discharges between the tool electrode and workpiece submerged in a dielectric fluid. Each discharge creates a high-temperature plasma channel capable of melting and vaporizing localized material, followed by debris removal through dielectric flushing. The process ensures minimal mechanical stresses on the workpiece and enables the machining of complex shapes, narrow slots, precision cavities, and high-aspect-ratio features that are otherwise challenging to achieve using conventional machining.

Despite these advantages, the machining of Inconel 718 through die-sinking EDM involves several unresolved scientific and technological challenges. The complex thermal–electrical interactions within the plasma channel often lead to **low material removal rate (MRR)**, **high tool wear rate (TWR)**, and **unstable spark behavior**. The rapid heating and cooling cycle generates a **recast layer** on the machined surface, which may contain **micro-cracks, voids, micro-globules, and hardened heat-affected zones**. Such defects can significantly affect the fatigue life, corrosion resistance, and structural integrity of components in critical applications. Additionally, the machinability of Inconel 718 is highly sensitive to process parameters such as discharge current, pulse-on time, pulse-off time, dielectric type, and electrode material. Understanding how these parameters interact with thermophysical properties of the alloy is essential for achieving optimum machining performance.

A comprehensive machinability analysis is therefore crucial to bridge the existing knowledge gaps related to EDM processing of Inconel 718. Such an analysis must incorporate not only conventional performance metrics—MRR, TWR, and surface roughness—but also detailed surface integrity evaluation, microstructural characterization, thermal 3odelling, and multi-response optimization. Furthermore, advancements in data-driven 3odelling, artificial intelligence, and multi-objective optimization techniques offer new opportunities to develop predictive frameworks and parameter-selection guidelines that enhance precision and efficiency.

This research aims to systematically investigate, model, and optimize the machinability characteristics of Inconel 718 under die-sinking EDM. Through a combination of experimental studies, microstructural analysis, and advanced 4odelling techniques, the study intends to deepen scientific understanding of spark erosion phenomena, establish correlations between process variables and material response, and propose optimized machining strategies suitable for high-performance industrial applications. The outcomes of this study are expected to contribute significantly to the fields of non-traditional machining, superalloy processing, and manufacturing of aerospace-grade components.

2. Review of Literature

Sahil Sharma et al (2022); The paper compares the influence of die-sinking EDM parameters on Alloy 625 and Alloy 718, focusing on MRR, TWR, and surface integrity. Results show Alloy 718 exhibits lower machinability with higher tool wear and thicker recast layers. Parametric sensitivity differs for both alloys, offering useful guidance for superalloy EDM processing.

Dikshit et al (2019); The study on die-sinking EDM of Inconel 625 examines how key process parameters—discharge current, pulse-on time, and pulse-off time—affect machining characteristics such as material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR). The results show that higher current and longer pulse-on time significantly increase MRR but also lead to greater tool wear and rougher surfaces due to intensified thermal erosion. The paper utilizes statistical methods, including Taguchi and regression analysis, to identify optimal parameter settings that balance productivity and surface quality. Overall, the study provides valuable insights for improving EDM performance when machining Inconel 625.

Kotha et al; (2025) Studies on die-sinking EDM of Inconel 718 consistently highlight its suitability for machining this difficult-to-cut superalloy due to the process's thermal erosion mechanism. Research employing Taguchi-based experimental designs, such as L27 arrays, demonstrates that parameters like peak current, pulse durations, flushing pressure, and servo voltage significantly influence MRR, SR, and surface integrity. Reported findings include improved MRR and reduced SR under optimized conditions. Surface analyses typically reveal recast layers, microvoids, and globules characteristic of EDM-induced melting and resolidification. Furthermore, recent works incorporate ANN models for performance prediction, with Bayesian Regularization often providing superior accuracy due to effective generalization capability.

E. Uhlmann et al; Research on machining MAR-M247, a directionally solidified nickel-based superalloy used in high-temperature turbine components, highlights its poor machinability due to high hardness, low thermal conductivity, and complex microstructure. Studies on die-sinking EDM for this alloy emphasize the need to control discharge energy, pulse characteristics, and dielectric conditions to minimize thermal damage while achieving acceptable productivity. The reviewed work focuses on developing an optimized EDM

strategy tailored to MAR-M247's thermophysical properties, examining responses such as material removal rate, tool wear, and surface integrity. The study reports improvements through parameter tuning and electrode selection, demonstrating that optimized EDM settings can significantly reduce recast layer thickness, micro-cracking, and residual thermal defects. Overall, the findings contribute to refining EDM technology for manufacturing turbine components where dimensional accuracy and metallurgical integrity are critical.

Singh, S. K et al; (2022) Studies on die-sinking EDM of Inconel 686 focus on optimizing key performance measures such as MRR, TWR, and surface roughness using statistical modelling techniques. Research employing Response Surface Methodology (RSM) with Central Composite Design (CCD) demonstrates that spark current, pulse-on time, duty cycle, and voltage significantly influence machining responses. ANOVA results typically confirm strong parameter–response correlations and high model adequacy for predicting EDM performance. Reported studies indicate reliable adequacy ratios and precision values for MRR, TWR, and Ra, validating the robustness of developed models. Overall, the findings highlight RSM as an effective tool for optimizing EDM parameters for Inconel 686.

3. Objectives of the Study

Primary Objective

To conduct a comprehensive and systematic analysis of the machinability characteristics of Inconel 718 during die-sinking EDM, and to develop optimized, scientifically validated machining frameworks aimed at enhancing process performance, surface quality, and overall machining efficiency.

Specific Objectives

1. To experimentally investigate the influence of key EDM parameters on MRR, TWR, surface integrity, and dimensional accuracy

   This objective focuses on studying how critical EDM input parameters—such as discharge current, pulse-on time, pulse-off time, servo voltage, dielectric flushing pressure, and electrode polarity—affect fundamental machining responses. The study will quantify the relationships between these parameters and key machinability metrics including Material Removal Rate (MRR), Tool Wear Rate (TWR), surface roughness, and dimensional deviation. This will enable the identification of dominant factors and their interactions under varying discharge energy conditions.

2. To study microstructural alterations including recast layer thickness, micro-cracks, and hardness variation using SEM/EDS/XRD.

   This objective aims to analyze the metallurgical changes induced by EDM's thermal cycles. Detailed surface integrity assessments will be performed by evaluating recast layer formation, crater morphology, micro-voids, and micro-cracks using Scanning Electron

Microscopy (SEM). Elemental migration and chemical modifications will be studied via Energy-Dispersive Spectroscopy (EDS), while X-Ray Diffraction (XRD) will be used to detect phase transformations and residual stress development. Microhardness profiling will help assess subsurface modifications and the extent of the heat-affected zone (HAZ).

3. To compare performance of various electrode materials (e.g., Cu, graphite, Cu-W).

   This objective includes evaluating the impact of different electrode materials on machining stability, tool wear behavior, electrical conductivity, and thermal characteristics. Various electrodes—such as copper, graphite, copper–tungsten, and possibly coated or composite electrodes—will be tested to determine their suitability for achieving higher MRR, lower TWR, and better surface finish. The comparative study will establish electrode-material performance maps for machining Inconel 718.

4. To develop predictive models using statistical and AI-based techniques.

   The aim is to build accurate, data-driven predictive models for MRR, TWR, surface roughness, and surface integrity parameters. Conventional statistical tools (e.g., RSM, ANOVA, regression modeling) will be combined with advanced AI techniques such as Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and machine learning algorithms. These models will help forecast machining behavior under unseen conditions and improve process predictability.

5. To optimize machining responses using multi-objective optimization strategies.

   This objective involves applying state-of-the-art optimization techniques—such as TOPSIS, MOORA, Grey Relational Analysis (GRA), Particle Swarm Optimization (PSO), or NSGA-II—to simultaneously maximize MRR and minimize TWR, surface roughness, and recast layer thickness. The goal is to identify the optimal parameter combinations that deliver the best compromise among conflicting machining objectives. Response surfaces and desirability functions will guide optimization.

6. To propose a machinability index for die-sinking EDM of Inconel 718.

   The final objective focuses on developing a composite machinability index that integrates multiple machining responses—MRR, TWR, surface quality, energy efficiency, and surface integrity metrics—into a single quantifiable score. This index will serve as a benchmarking tool for evaluating overall machining performance and could be applied for comparative studies across different materials, electrode types, and EDM setups.

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4. Significance of the Study

- **Addresses the major industrial challenge of machining Inconel 718 for aerospace and energy components.**

Inconel 718 is widely used in turbine blades, combustion chambers, rocket engine parts, and high-temperature structural components. However, its exceptional strength, work-hardening tendency, and poor thermal conductivity make it one of the most difficult materials to machine using conventional processes. This research directly addresses these industrial challenges by proposing optimized die-sinking EDM strategies, enabling more efficient, accurate, and sustainable machining of critical aerospace and energy-sector components.

- **Enhances scientific understanding of spark-eroded surface formation and thermal damage mechanisms.**

EDM involves rapid thermal cycles, leading to complex surface phenomena such as recast layer formation, micro-cracks, resolidified debris, and metallurgical transformations. This study provides a deeper scientific understanding of these spark-induced alterations by examining crater morphology, elemental migration, heat-affected zone behavior, and microstructural defects through advanced characterization tools like SEM, EDS, and XRD. The resulting insights help establish clear relationships between discharge energy, thermal gradients, and surface integrity.

- **Contributes to the development of predictive and optimization models for real-world applications.**

By integrating statistical modelling, AI-based prediction techniques, and multi-objective optimization algorithms, the study aims to create robust predictive frameworks for die-sinking EDM. These models allow manufacturers to accurately forecast machining performance under varying parameter conditions, reduce experimental trial costs, and implement data-driven decision-making. The research outcomes support real-world applications by guiding industries toward high-performance machining strategies with improved reliability and consistency.

- **Provides guidelines to industries for improving productivity and part quality while minimizing tool wear and defects.**

The research outcomes will serve as practical guidelines for optimizing EDM parameters to maximize material removal rate while reducing tool wear, dimensional errors, recast layer thickness, and micro-cracks. These guidelines enable industries to achieve higher productivity, better surface finish, and extended tool life. Ultimately, the study contributes to cost reduction, improved process stability, and enhanced part quality across aerospace, defense, and energy manufacturing sectors.

- **Advances non-traditional machining research and supports development of high-performance superalloy components.**

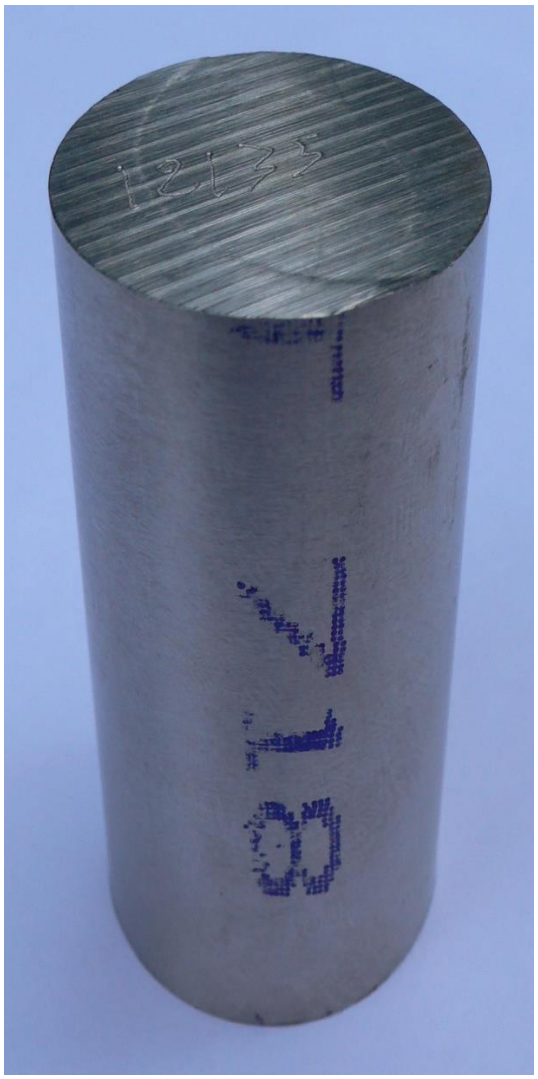
By focusing on Inconel 718—one of the most critical superalloys used globally—this research strengthens the scientific foundation of non-traditional machining technologies. The findings contribute to the broader advancement of EDM as a precision manufacturing method for next-generation materials. This work also supports the development of high-performance superalloy components by offering improved machinability insights, optimized process

windows, and enhanced surface integrity strategies tailored for critical engineering applications.

5. Study Area

The study will focus on:

- Machining Inconel 718 specimens using die-sinking EDM.
- Experimentation carried out in the manufacturing lab using standard EDM equipment.
- Surface integrity analysis in materials characterization laboratory (SEM, EDS, optical profilometer, hardness tester).
- Modeling and optimization.



INCONEL 718

CNC EDM

6. Methodology of Research Work

Phase 1: Problem Identification & Literature Review

- Comprehensive review of EDM and Inconel 718 machining studies.
- Identification of research gaps and defining parameters/responses.

Phase 2: Experimental Design

- Selection of process parameters:
    - Discharge current
    - Pulse-on time
    - Voltage
- Design of Experiments (DOE) using Taguchi / RSM.

Phase 3: Experimental Investigation

- Conduct die-sinking EDM trials on Inconel 718 blocks.
- Measure machinability responses:
    - MRR
    - TWR
    - Surface roughness (Ra)
    - Dimensional accuracy (Cylindricity, Taperness Etc.,)

Phase 4: Surface Integrity Analysis

- Microscopic and metallurgical evaluation:
    - Recast layer thickness
    - Micro-cracks and voids
    - Elemental migration (EDS)
    - Microhardness profiling

Phase 5: Modeling and Prediction

- Regression modeling
- Artificial Neural Networks (ANN) / Machine Learning models
- Multi-physics conceptual model of spark erosion (if applicable)

Phase 6: Optimization

- Multi-objective optimization (e.g., TOPSIS, MOORA, NSGA-II).

- Development of machinability index.

Phase 7: Validation and Thesis Compilation

- Model validation with confirmatory experiments.
- Documentation and conclusi

7. Expected Outcomes

- A complete machinability map of Inconel 718 under die-sinking EDM conditions.
- Optimized parameter sets for improved MRR, reduced TWR, and enhanced surface quality.
- Detailed understanding of surface integrity, recast layer, and thermal effects.
- Predictive AI models linking process parameters to machining performance.
- A proposed machinability index for industrial use.
- Publications in SCI/Scopus-indexed journals.

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